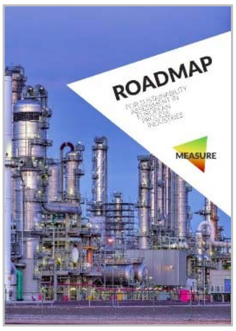
Background document

supplementing the

“Roadmap for

Sustainability Assessment in

European Process Industries”



Current State of LCSA

Authors:

N. Minkov[1], M. Finkbeiner[1], S. Sfez[2], J. Dewulf[2], A. Manent[3], E. Rother[3], P. Weyell[4], D. Kralisch[4], D. Schowanek[5], A. Lapkin[6], M. Jones[7], A. Azapagic[7]

[1] Technical University of Berlin, Department of Environmental Technology, Chair of Sustainable Engineering

[2] Ghent University, Research Group ENVOC

[3] Evonik Technology & Infrastructure GmbH, Life Cycle Management

[4] Friedrich-Schiller-University Jena, Institute of Pharmacy, Department of Pharmaceutical Technology

[5] Procter & Gamble Services Company NV, Global Product Stewardship

[6] University of Cambridge, Department of Chemical Engineering and Biotechnology

[7] The University of Manchester, School of Chemical Engineering and Analytical Science

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1 Introduction

The present background document provides an overview of current methodological developments in the context of Life Cycle Sustainability Assessment (LCSA), which are of general importance for all sectors covered within the MEASURE project and the ultimate outcome of the project – the “Roadmap for sustainability assessment of the European process industries”. It summarizes the success in developing and implementing methods and tools to evaluate the three pillars of sustainability, the intrinsic problems of sensitivity and uncertainty, available databases as well as recent progress in coupling LCSA with other established methods and tools such as engineering tools or methods for multi-criteria decision making. The last section of the document provides a short description of the Product Environmental Footprint (PEF) Initiative of the European Commission and its relation to SPIRE and MEASURE.

2 Challenges in achieving full life cycle sustainability assessment

2.1 Introduction

The importance of the environmental aspect of sustainability is already recognized by mainstream business practices in many sectors. Challenges relating to e.g. resource depletion or the emission of GHG are attracting increasing attention owing not least to regulatory, supply chain, reputational and consumer pressure (Spence, Agyemang et al. 2012). However, the global society has undergone a paradigm shift from pure environmental protection towards sustainability and resilience (i.e. the potential to adapt to rapidly changing and fluctuating situations). There is a common agreement that sustainability does not only focus on the environmental impact. It rather consists of the three dimensions “environment”, “economy” and “social well-being”, for which society needs to find a balance or even an optimum (Finkbeiner, Schau et al. 2010).

Since sustainability is a global concept that involves present and future generations, this inevitably calls for a system-wide analysis (Zamagni 2012). A system perspective is at the core of the life cycle approach, which can provide valuable support in the sustainability evaluations, as demonstrated by the numerous environmental policies at for example European level, which are based on the life cycle concept. Moreover, the SPIRE Roadmap has set targets, the achievement of which requires the use of a life cycle analysis to consider effects along the value chain and to demonstrate sustainability advantages.

In this regard, Life Cycle Assessment (LCA) is considered to be one of the most appropriate and robust assessment frameworks for the evaluation of the potential impacts of a product’s entire life cycle – from raw materials extraction to final disposal. Because it is holistic, systematic and rigorous, LCA in general is the preferred tool when it comes to access information about potential impacts of products along their life cycle.

However, products are also linked to production and consumption impacts on the workers, the local communities, the consumers, the society and all value chain actors (Benoît and Mazijn 2009). In this regard, Social Life Cycle Assessment (SLCA) has gained popularity in the recent years as an approach aiming at evaluating social and socioeconomic aspects and their potential positive and negative impacts over the life cycle of products (Benoît and Mazijn 2009, Zamagni, Amerighi et al. 2011). In economic terms, Life Cycle Costing (LCC) gives the possibility to identify economic hotspots, which can be valuable for the decision making process within a full sustainability assessment.

In combining those, a sustainability and life-cycle based approach can be integrated under a LCSA framework. The method is under establishment in the recent years, consisting of a contemporary implementation of (environmental) LCA, LCC and SLCA. In this section, the development of LCA, LCC and SLCA is overviewed together with their current limitations. A short overview on the concept of LCSA is also provided.

2.2 Development and limitations

2.2.1 General LCA and the environmental perspective

Work on LCA began in the 1960s in the US, when concerns over the limitations of raw materials and energy resources sparked interest in finding ways to cumulatively account for energy use and to project future resource supplies and use. Interest in LCA waned from 1975 through the early 1980's, because environmental concerns shifted to issues of hazardous and household waste management. But when solid waste became a worldwide issue, LCA again emerged as a tool for analysing environmental problems.

By 1991, concerns over the inappropriate use of LCAs by product manufacturers to make broad marketing claims made it clear that uniform methods for conducting such assessments were needed. A consensus was also required on how this type of environmental comparison could be advertised non-deceptively. At the same time, pressure was growing from a number of environmental organizations to standardize LCA methodology. This led to the development of the LCA standards in the ISO 14000 series (1997 through 2006) (ALCAS 2015).

In 2002, the United Nations Environment Programme (UNEP) joined forces with the Society of Environmental Toxicology and Chemistry (SETAC) to launch the Life Cycle Initiative as an international partnership (UNEP/SETAC 2015). The Life Cycle Initiative's main aim was formulated as putting life cycle thinking into practice and improving the supporting tools through better data and indicators.

LCA is governed today by the ISO 14040/44 series of standards (ISO 2006a, ISO 2006b). As shown in Figure 1, an LCA study consists of four main phases: Goal and scope definition; Life Cycle Inventory Analysis (LCI); Life Cycle Impact Assessment (LCIA) and Interpretation.

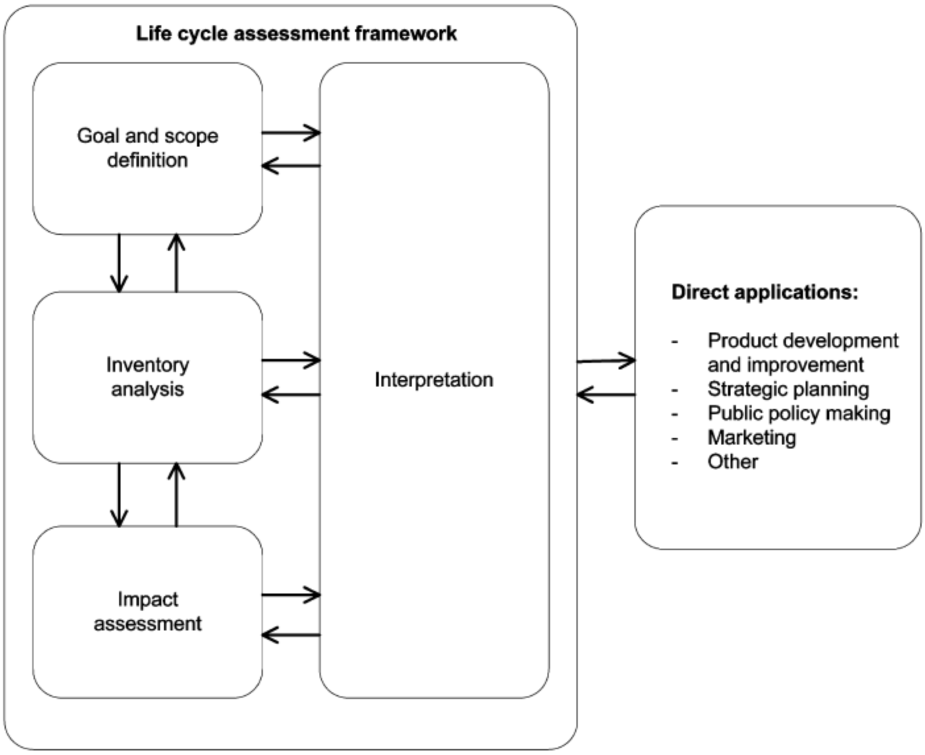

Figure 1: General methodological framework for LCA (ISO 2006a).

Currently, environmental LCA is considered to be rather mature and well developed. However, gaps and limitations still exist. Although the framework and procedures are well defined by ISO14040/14044, the complexity of methods and the variety of challenges and choices (methodological, data-related, etc.) makes it a time consuming expert task (Reap, Roman et al. 2008a, Reap, Roman et al. 2008b). Therefore, the following section is based on Finkbeiner et al. (Finkbeiner, Ackermann et al. 2014), being the most recent and complete analysis. The authors developed a book chapter summarizing the content, relevance, state of the art literature, and potential solutions of 34 gaps and challenges of environmental LCA. Based on over 50 pages of analysis, they encompass the gaps and challenges, divided by four aspects:

- Inventory aspects
    - Water use and consumption
    - Renewable energy
    - Biogenic carbon
    - Delayed emissions
    - Improbable events
    - Allocation
    - Functional unit
- Impact assessment aspects
    - Human health: human toxicity, direct health effects, particulate matter, nanomaterials, microbiological pollution, noise and odour
    - Ecosystem: ecotoxicity, biodiversity, biological invasion, direct non-intended killing of animals, land use and land use change

  - Resources: abiotic and abiotic resources, change in soil quality, desertification, salinization
- Generic aspects
  - Data quality analysis
  - Uncertainty analysis
  - Weighting
  - Macroeconomic scale-up
  - Modelling approach: consequential LCA
  - Rebound effects
- Evolving aspects
  - Positive impacts
  - Animal well-being
  - Littering

The authors conclude that the identified methodological gaps can have a significant influence on the results of LCA studies, even though not every individual case study suffers from all 34 gaps. Users and decision makers face a complex situation until the solutions are developed, as the relevance of the gaps depends on the products studied and the intended application of the LCA.

A number of challenges, e.g. 'allocation', 'functional unit' or uncertainty, is inherent to the LCA method as such. The authors indicate that while many of the challenges identified above can be addressed by future scientific work and progress, these three fundamental challenges may inherently require value choices. These choices can be scientifically informed, more pragmatic or more theoretical, but they remain value choices.

In conclusion, the study envisages that a recurrent topic for many challenges identified in LCA is the need for additional, robust and relevant data. This is a task for practitioners and stakeholders, not only for science. Secondary data sets used in the comparative studies should derive from the same source and offer the same level of detail in the coverage of inventory flows for all the materials under evaluation.

2.2.2 Social aspects in LCA

The inclusion of social aspects in LCA has not undergone significant improvements until the early 2000, when the first approaches have been presented (Ramirez and Petti 2011). The interest on and the development of SLCA has grown quickly in the recent years, mainly after the publication of the Guidelines for SLCA (Benoît and Mazijn 2009), which follow the framework of the ISO standard for LCA (Lehmann, Zschieschang et al. 2013). The Guidelines present key elements to consider and provide guidance for the goal and scope, inventory, impact assessment and interpretation phases of a SLCA. The framework proposes a two-fold classification of social impacts: by stakeholder categories and impact categories. Ultimately, the document also highlights areas for further research.

Further, in 2013 the Roundtable for Product Social Metrics has been established aiming at harmonizing principles, methodologies, impact categories and performance indicators for product social impact assessment. As a result, the Handbook for Product Social Impact Assessment (Fontes 2014) has been published together with the outcomes of pilot studies of six different products. The Handbook is based on the Guidelines for SLCA and corporate level standards as GRI (GRI 2011) and ISO 26000 (ISO 2010). The proposed assessment method provides 1) a more pragmatic approach to assess social issues at the product level; 2) a set of metrics and indicators for each stakeholder category, and 3) a method to convert performance indicators to the reference unit.

Apart from the Handbook, no considerable progress has been made since the release of the Guidelines in the last five years, despite the numerous published papers dealing with methodological development and case studies, e.g. (Lehmann, Russi et al. 2011, Jørgensen 2013, Finkbeiner, Ackermann et al. 2014, Martínez-Blanco, Lehmann et al. 2014). There is still no complete and broadly accepted methodology for SLCA (Martínez-Blanco, Lehmann et al. 2014). Moreover, limitations can be listed on both inventory and impact assessment level. Two main reasons could cause the lack of development, according to Norris (Norris 2014): 1) confusion on the goal and scope, and 2) lack of data and practical tools. As a third pillar, the impact assessment step is distinguished below as well. However, for the chemical industry there are several guidelines for social metrics currently under development, for example by the World Business Council for Sustainable Development (WBCSD) chemical sector group or the "Chemie³" initiative in Germany.

2.2.2.1 Goal and scope

The diversity of goals and scopes creates incentives for the development of different methodologies and might be the underlying reason behind the multiplicity of approaches to SLCA (Norris 2014). Such diverse purposes may be e.g. is the study intended for comparison, or decision support, or for identification of hotspots; is it part of a broader sustainability assessment or a stand-alone SLCA, etc.

Since SLCA is based on a perspective that links the socioeconomic impacts to the behaviour of a company (further described below), indicators can hardly be referred to the functional unit (Parent, Cucuzzella et al. 2010). In this context, Zamagni et al. (Zamagni, Amerighi et al. 2011) questioned the requirement of a functional unit approach and a company perspective within the same framework, i.e. "…as the goal is the improvement of social aspects related to a product system, is it appropriate to apply the functional unit concept in the same way as we do in environmental LCA – hence to relate the social performance to the unit processes directly involved" (Zamagni, Amerighi et al. 2011). To overcome this main challenge of SLCA, Martínez-Blanco et al. (Martínez-Blanco, Lehmann et al. 2014) proposed organizational approach of SLCA to complement existing SLCA by enhancing the scope and by making them more applicable.

2.2.2.2 Data and tools

With regard to the inventory, two main challenges occur: data collection and linking social indicators and impacts to a product (via the functional unit). Data on social events is hard to gather and usually vary sector- or country specific. It is also possible that the same product, produced in different parts of the world can cause different social impacts (Zamagni, Amerighi et al. 2011) and therefore, the data demand and analysis of different aspects will differ, too. Many site-specific data are required, which is costly and not efficient. Furthermore, Martínez-Blanco et al. (Martínez-Blanco, Lehmann et al. 2014) highlighted that, if data are to be collected on a company level, the required resources would be very high, as many companies have to be involved.

Moreover, databases such as for environmental LCA do not yet exist. One is the Social Hotspot Database (SHDB 2015) containing few datasets, but it only provides generic data and information on risks that social impact may occur in a certain country or sector. To assess the social performance of a particular product, site-specific data would be needed. Thus, various authors recommend to use the SHDB as a first step to identify hotspots and then to focus on these hotspots for further site-specific data collection.

The second main challenge relates to referring the data to the FU. Whereas environmental LCA mainly focuses on collecting information on (mostly) physical quantities related to the product over its life cycle stages, SLCA collects additional information on organization related aspects along the chain (Benoît and Mazijn 2009). Due to this usual reference to the organization's behaviour, it is still hardly feasible to allocate social indicators and impacts to the product level (Martínez-Blanco, Lehmann et al. 2015). As a proof, Martínez-Blanco et al. (Martínez-Blanco, Lehmann et al. 2015) analysed the proposed indicators of the Methodological sheets (UNEP/SETAC 2013) of the Guidance for SLCA, resulting in only 8 indicators out of the 189 recommended showing a direct relation to the product level.

In addition, in contrast to the environmental LCA, SLCA indicators can be not only quantitative, but also qualitative and semi-quantitative (Neugebauer, Martinez-Blanco et al. 2015). In some cases, the set of qualitative and/or semi-quantitative can be even larger than the quantitative. This poses other challenges regarding the relation to the FU.

2.2.2.3 Impact assessment

So far, no agreed impact assessment methods exist. Parent et al. (Parent, Cucuzzella et al. 2010) distinguished between two types of social impact assessment (with and without the use of causal-effect chains[1], also known as 'reference points').

Social sciences do not currently provide many well-established impact pathways allowing the assessment of a particular impact to a specific and documented action tied to a unit process (Norris 2014). Several impact categories have been proposed during the years, but they are still under discussion due to the lack of clearly defined impact pathways. Moreover, the focus

[1] A causal-chain impact is an impact directly attributed to the production activity itself.

so far has been put on the representation of stakeholder groups without bridging the gap towards impact assessment (Finkbeiner, Ackermann et al. 2014).

Choosing between the feasibility of deriving social impacts from social variables through impact pathways or assessing a broader set of social issues through the use of qualitative or semi-quantitative indicators is still an ongoing issue and requires further research in a medium and long-term perspective (Parent, Cucuzzella et al. 2010).

Furthermore, agreement on many criteria for social aspects is very hard to be found, due to the influence of different values and ethics for different cultures. The example given by Martínez-Blanco et al. (Martínez-Blanco, Lehmann et al. 2014) perfectly describes how criteria can vary significantly between sectors and regions, by stating that "…a low share of female workers in a certain sector does not necessarily indicate a 'risk for discrimination', but can result simply from the type of work, for instance mining".

Overall, current SLCA case studies define criteria/reference points and relate the results to this, resulting to "traffic light system" outcomes, rather than quantified results that can be easily interpreted.

2.2.3 Economic methods in LCA

When it comes to economic evaluations, the situation is not as straight forward as in the case with environmental and social aspects. Therefore, the current section overviews several methods that can be coupled with the life cycle perspective. However, at the company level economic assessments for products and product developments are well established.

2.2.3.1 Life-Cycle Costing

LCC, also called Environmental Life Cycle Costing (eLCC), approach has been developed to be used in parallel with LCA in a consistent manner (Swarr, Hunkeler et al. 2011). It summarizes all the costs associated with the life cycle of a product or service that are directly covered by one, or more, of the actors in the product life cycle (e.g. supplier, producer, user/consumer, end-of-life actor). In this context, costs are defined as the monetary value of goods and services that producers and consumers purchase. The SETAC LCC working group, established in 2003, mainly pushed its development. The goal of this group was to write a „Code of Practice" (Swarr, Hunkeler et al. 2011) for LCC similar to the existing "Code of Practice" (Consoli, Allen et al. 1993) for LCA and to build consensus for an international standard parallel to the ISO 14040 standard. The intention of the strong orientation on the LCA methodology was to put LCC on a solid basis, and lay the foundation for eventual integration of SLCA into a comprehensive three-pillar assessment (LCSA).

The SETAC group proposed that a LCC consists of the same phases (goal and scope definition, inventory and impact assessment as well as interpretation) and refers to the same functional unit as for LCA. Many critical issues of LCA studies such as allocations, dependence of the outcome from stakeholder perspectives or regional variations as well as ensuring data quality occur in LCC studies as well. The system boundary must not be identical but equivalent.

However, unlike LCA, there is no need for characterization or weighting of inventory data, because all inventory data comprise a single unit of measure, namely currency. (Swarr, Hunkeler et al. 2011)

Despite the continuous methodological developments of the LCC analysis over the last years, LCC is so far seldom used in process industries or academia to decide between alternative technologies. Where used, it is mostly combined with the evaluation of environmental impacts. Thus, various methodologies exist to quantify and represent eco-efficiency, the ratio between environmental pressure and economic growth. However, not all of them follow the life-cycle concept. Instead, critical comments in the literature argue that so far there is no standardized way to perform an eco-efficiency analysis.(Ng, Yeo et al. 2015) In the following part, some examples are given to show the broad range of existing approaches. The eco-efficiency analysis, used by BASF, follows the LCC concept. It has been developed to provide information about the relationship between economic benefits of a product or technology and its impacts on the environment along the entire supply chain and throughout all of its lifecycle stages (Uhlmann and Sahling 2010). One intention for this coupling is the provision of the necessary data to support internal investment and product portfolio decisions. The costs of raw materials, labor, energy, capital investment, maintenance activities, transportation, illness and accidents as well as waste disposal are included among others to determine the total life cycle costs. In other studies, e.g. the Net Present Value, the Economic Value Added, opportunity costs or eco-efficiency scores have been used to calculate the economic impacts of alternative production pathways compared to environmental impacts in eco-efficiency analyses (Czaplicka-Kolarz, Burchart-Korol et al. 2010, Hahn, Figge et al. 2010, Guenster, Bauer et al. 2011, Picazo-Tadeo, Beltrán-Esteve et al. 2012).

Independent from the harmonization need, the relevance of full LCC in sustainability assessment as the most elaborated method to assess the economic part of eco-efficiency analysis so far has been debated and questioned in literature (Jørgensen, Finkbeiner et al. 2010, Sala, Farioli et al. 2013). Arguments are on the one hand that by focusing mainly on the costs for the individual, it fails to take into account the broad (global) perspective inherent to sustainability. On the other hand, by addressing monetary costs, it fails to consider the different capitals relevant to sustainability. However, one has to take care of the purpose and stakeholder perspective of an LCC or eco-efficiency study before raising those arguments. They are true from a broad societal or political perspective, but, e.g., a decision for an investment in a novel technology naturally requires a business perspective to convince decision makers to decide for the more sustainable alternative. Here, the calculation of opportunity costs, e.g. the Sustainable Value Added, can support the more detailed LCC study. The method developed by Figge (Figge and Hahn 2002) measures whether a company can create extra value, expressed in monetary terms, without causing additional environmental or social impacts. Settanni (Settanni 2008) further argues that a computational structure of LCC would help in overcoming existing methodological and implementation-related inconsistencies that may arise when using LCC in environmental management and especially in combination with LCA.

Despite all critics and open issues, LCC and eco-efficiency analyses in general are seen in the current literature as valuable concepts to maximize value creation while minimizing the use of resources and emissions of pollutants. It offers an integrated management framework of concepts, techniques and procedures to think how to best operationalize sustainable actions to achieve the identified business value (Harbi, Margni et al. 2015). However, future efforts in methodological improvements, standardization and better adaption to corporate operational decision making are needed to gain a wider acceptance (Dyckhoff, Quandel et al. 2015).

2.2.3.2 Economic Input-Output-LCA

The concept of Economic Input-Output Life Cycle Assessment (EIO-LCA) method can be seen as alternative to eco-efficiency analyses, when it comes to the assessment of dependencies between environmental impacts and costs on a supply chain or sector level (Hendrickson, Lave et al. 2010). The EIO-LCA estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in industry (Gottschalk, Kost et al. 2013). The method is based on information about industry transactions and the information about direct environmental emissions of industries. It takes into account the total emissions throughout the supply chain. The combination of LCA and EIO is done based on a mathematical model, linking several levels of suppliers. Thus, the demand of output from the first-tier of suppliers creates a demand for output from *their* direct suppliers (i.e., the second-tier suppliers of the sector).

Although the method is well-suited for cross-sectorial evaluations, it comes also with some limitations. Since the results represent impacts through the production of output by the sector with increased demand, the use phase and end-of-life phases are typically not included in the results. Uncertainties in data sources, limitations in the consideration of LCIA methods and others add to current shortcomings of the method developed by the Carnegie Mellon University. However, the overall concept can help to get valuable insights on the relationship between economic growth and environmental protection in a holistic manner. Thus, further improvements of the methodology and a better linkage to existing LCA software tools are strongly recommended in order to induce a more widespread use.

2.2.3.3 Full cost accounting

In addition, there is a motivation for performing cost studies in the context of sustainability assessment to fully account for the financial costs of life-cycle environmental aspects as well as economic impacts that ultimately result from a decision. This can be achieved by internalizing the costs by applying the polluter pays principle. Typically, only those costs that are likely to be internalized in the decision-relevant period are monetized in this context (Swarr, Hunkeler et al. 2011). According to Jones (Jones 2010), the current accounting in companies is incompatible with such a kind of environmental accounting. Gray (Gray 2013) points out that conventional financial accounting is a predominantly economic practice that has no substantive conceptual space for environmental or social matters per se, too. In the first place, the term ‘‘environment’’ as it is manifest in financial accounting, is typically taken to reflect a range of costs, liabilities or potential risks/opportunities that derive, at some point at least, from matters perhaps conveniently thought of as deriving from the natural environment in some way or other. However, in terms of a sustainable development, also unavoidable costs due to social and environmental damage and capture should be recognized besides growth, efficiency and profit. Thus, full cost accounting was developed to adjust the existing prices of products and services by monetizing and incorporating both internal and external impacts (positive and negative), including environmental and social externalities (Bebbington 2001).

2.2.3.4 Avoidance & restoration costs

An additional approach is the exclusive calculation of external costs by turning environmental (and social) effects into monetary values. Example are the “cost of control approach” (CICA 1997), which provides monetised values for the cost of installing and operating pollution control mechanisms that will control the pollution to a prescribed level, or the calculation of eco-costs (Vogtlander and Bijma 2000). The latter is going beyond the cost of control approach, being a measure to express the amount of environmental burden of a product on the basis of preventing that burden, so it is the sum of all eco-costs of emissions and use of materials during the life cycle "from cradle to grave" of a product or service. Those eco-costs are virtual (external) costs, they are consequently not integrated in LCC analyses. However, also the eco-cost approach can be extended to a kind of eco-efficiency analysis by calculating the Eco-costs/Value Ratio (EVR) (Vogtländer, Lindeijer et al. 2002).

2.2.4 Full life cycle sustainability assessment

Kloepffer (Kloepffer 2007) has put the LCSA framework into the formula: LCSA = LCA + LCC + SLCA. In order for the equation to be valid and the three pillars to be evaluated together, they all shall have common goal and scope defined (Valdivia, Ugaya et al. 2013), including identical functional unit and equivalent system boundaries (cut off criteria can be used and can be different for each technique). Ideally, the three assessments methods should be standardized, not only LCA. To date, there is no standardized methodology for the execution of LCSA.

Alternatively, a year later Kloepffer (Kloepffer 2008) proposed a second option of the performance of LCSA, namely, to include LCC and SLCA as additional impact categories to an already developed LCA. This means that the three dimensions are to be based on the same LCI, which could be considered as the advantage of this approach, but not that straightforward to be achieved in reality.

Despite the two options, Valdivia et al. (Valdivia, Ugaya et al. 2013) listed some potential benefits of combining the three techniques towards an LCSA, including cost reduction (as some data can be collected at the same time), risk reduction of double counting, consistency in the reporting (as the results of the three techniques are based on the same functional unit) and motivated and better engaged stakeholders, especially in developing countries, following iterative consultative processes.

In terms of impact assessment so far, a commonly accepted set of indicators of LCSA has not been identified among the current LCSA initiatives and approaches (Valdivia, Ugaya et al.

2013). A recent study by Neugebauer et al. (Neugebauer, Martinez-Blanco et al. 2015) provided a ranking of different indicators used in LCA, LCC and SLCA, according to their practicability, relevance and method robustness. The objective is to overcome the barrier of complexity for the implementation of LCSA.

The development process at theoretical and conceptual level is still ongoing, but the preliminary steps for its operationalization are set (Zamagni, Pesonen et al. 2013). Further challenges have not been addressed herewith, as the ones discussed under the particular sustainability dimensions above are in full force when considering LCSA.

2.2.5 Conclusion

LCA is now approaching mainstream. After many years of method development, case studies, international standardization, database and software development, environmental LCA is mature and robust enough to inform decision-making – in both private and public organizations. LCA is currently the most accepted tool to assess the environmental performance of products and this basically applies all around the globe and to all stakeholders, e.g. government, industry, non-governmental organizations (NGOs) and academia (Finkbeiner, Ackermann et al. 2014). However gaps still exist. Both, the international standards of LCA and the scientific literature are quite transparent with regard to the gaps and challenges of the method. LCA does not provide the 'full environmental truth', at least not just yet. ISO 14040/44 standards acknowledge clearly that any LCA study has its limitations (Finkbeiner, Ackermann et al. 2014). However, LCA will be elaborated in many directions in the next decade. Regionalized databases will be developed, new impact assessment methods will be designed, and methods for uncertainty analysis will be improved (Guinee, Heijungs et al. 2011)). Despite the large number of gaps and challenges identified, LCA is still the "…best framework for assessing the potential environmental impacts of products currently available" (EU 2003).

While environmental LCA is a standardized method (by ISO 14040), SLCA still suffers lack of scientific consensus and definitions, including proper impact assessment and thus, broader practical implementation (Neugebauer, Martinez-Blanco et al. 2015). The challenges regarding the inventory, limited data availability and lack of applicable methods and tools result in an absence of studies that address completely the life cycle of a product; they often just focus on one life cycle phase. Similar conclusions can be drawn by the joint SPIRE survey (SPIRE – Sustainability Tools Survey 2015 – see **background document** "MEASURE survey results"). Whereas around 80% of the industry answered positively if they perform environmental LCA, SLCA is performed only by less than 20%. In this regard, SLCA is considered to be not fully operational today. To establish the approach as a useful and operation tool, further development studies on a wide range of products is needed (Zamagni, Amerighi et al. 2011, Lehmann, Zschieschang et al. 2013, Martínez-Blanco, Lehmann et al. 2014).

In terms of the economic dimension, a plethora of methods to assess the economic aspects of sustainability exist, ranging from cost accounting of internal costs over mixed types to exclusive calculation of external costs, but they still lack consistent terminology and methodological harmonisation.

While sustainability is nowadays accepted by all stakeholders as a guiding principle, the challenge to unambiguously determine and measure sustainability performance does remain, especially for products and processes. The maturity of methods and tools is different for the three sustainability dimensions. While the environmental dimension can be covered quite well today, the economic and social indicators and evaluation methods still need fundamental scientific progress (Finkbeiner, Schau et al. 2010, Neugebauer, Martinez-Blanco et al. 2015). The number of applications of LCSA is still limited, and the majority of the examples occur at the interface of environmental and economic aspects (Zamagni, Pesonen et al. 2013).

3 Overview of methods, tools and databases currently used in LCSA

3.1 Summary of the most established tools and LCIA methods

Based on two stakeholder surveys and the stakeholder analysis conducted within the WP2, several tools for sustainability assessment have been identified as being the most used in process industries. LCIA methods used within the purpose of an LCA have also been investigated. All these tools require a high level of expertise and are applied by sustainability experts from academics and industries.

In the following Table1 and Table 2, these tools and LCIA methods are described and briefly analysed based on their system boundaries, specific data requirement, their acceptance and the pillar of sustainability they covered. Additional approaches are also described, due to their large public interest and potential influence on policy and market in the EU. Acceptance and spread was determined based on the results of the first survey (more information can be found in **background document** “MEASURE survey results”) and on the discussions hold during the first Workshop in Mechelen. Every tool and LCIA method presented here can cover the complete life cycle of products (cradle-to-grave) except the cradle-to-cradle assessment.

Table 1: Summary of the most established tools for sustainability assessment

Assessment Tools	Description	Fundamental documents	Specific data required or database	Pillar of Sustainability	Acceptance & spread based on MEASURE surveys
Life Cycle Assessment (LCA)	LCA is a method that measures a wide range of environmental aspects related to a product, process or service. LCA addresses the environmental aspects and potential environmental impacts throughout a product's life cycle, i.e., from raw material extraction, to production, use and end-of-life treatment (also known as cradle-to-grave analysis) According to the ISO-guidelines (14040/44), an LCA consists of 4 phases: Goal and scope definition; Life Cycle Inventory Analysis (LCI); Life Cycle Impact Assessment (LCIA); Interpretation.	ISO 14040, 2006a ISO 14044, 2006b UNEP 2003	Ecoinvent database EU database ELCD GaBi database Etc.	Environment	Widely accepted and used (63% of respondents use it regularly and 24% irregularly)
Carbon Footprint	Carbon Footprint can be used at product, process and organizational level. It measures the total greenhouse gas emissions caused directly and indirectly.	Pertsova 2007	Same databases as LCA	Environment, focus on Greenhouse gases emissions	Widely accepted and used (47% of respondents use it regularly and 22% irregularly)
Cumulative Energy Demand (CED)	Direct and indirect energy use, including the energy consumed during the extraction, manufacturing and disposal of the raw and auxiliary materials. Direct energy inputs refer to primary energy input required for manufacture, use and end-of-life in life cycle. Indirect energy inputs are all inputs that are used for other purposes than manufacturing product, such as infrastructure and equipment.	VDI 1997 Frischknecht et al, 1998	Same databases as LCA	Environment: focus on resource consumption	Widely accepted and used (36% of users among respondents from industries and 58% from other sector)

Cost Benefit Analysis (CBA)	CBA is a decision support tool, which aims at evaluating the costs and benefits of a project for society in terms of monetary values. Additionally to financial accounting, it is based on the concept of monetization, which consists in translating externalities, i.e. non-market outputs produced by a project, in monetary terms.	Edwards-Jones et al. 2000 EC 2014	Several databases need to be used (e.g. TREMOVE database for emissions from different vehicle category; EVRI databases for benefit transfer etc.)	Environment, Economic, Social	Few users (25% of users respondents use it regularly, and 36% irregularly)
Ecological Footprint (EF)	The EF is a LCIA method. It describes the area of biologically productive land and water that a product, an organization or a population needs to produce the necessary resources it consumes and to absorb the waste it produces. It thus gives an idea of the regenerative capacity of the biosphere that is needed to compensate for the use of resources by the product, the organization or the population. The ecological footprint is expressed in Global hectares, which is the amount of biological service consumed per unit of time (global hectare * years).	Ewing et. al 2010 Global Footprint Network	Database provided by the Global Footprint Network	Environment	Few users (24% of respondents use it regularly and 20% - more established in non-industrial sectors) Good acceptance in non-industrial sectors.
Life Cycle Costing (LCC)	LCC is an economic approach that sums up the total costs of a product, process or activity discounted over its lifetime.	Hunkeler et al., 2008 Swarr et al. 2011	Product life-cycle economic data	Economic	Few users (17% of respondents use it regularly and 32% irregularly). Good acceptance.
Full cost accounting	Full cost accounting summarizes the internal financial flows associated with performance in the economic, social and environmental dimensions of sustainability. The information is extracted from existing accounting systems and shows the sustainability related elements of current expenditure.	Bebbington 2001	Internal economic data	Environment, Economic, Social expressed in monetary value	Few users Acceptance could not be evaluated

Eco-costs	Eco-costs account for restoration and avoidance values, thus considering costs and benefits (externalities) that are not currently accounted for by the institution	Vogtlander et al. 2000	Economic restoration and avoidance values	Environment expressed in restoration and avoidance costs	Few users Acceptance could not be evaluated
Water Footprint (WF)	WF analyses the freshwater consumption and degradation along a product's life cycle and associated impacts. 'Water use' is the total input of freshwater into a product system, whereas 'water consumption' is the difference between water in- and outputs, e.g. the amount of water "lost" due to evaporation or product integration. WF is a geographically explicit indicator, not only showing volumes of water consumed and pollution, but also the locations and timing of the action. WF consists of three components: blue water (surface water and ground water), green water (rainwater stored in the soil as soil moisture), grey water (volume of polluted water associated with the production).	DIN ISO 14046, 2014 Pfister et al., 2009 Hoekstra et al., 2011 Berger et al., 2014 Water Footprint Network	WaterStat database provided by the Water Footprint Network WAVE (Water accounting & vulnerability evaluation) model	Environment with focus on the water resource	Few users (14% of respondents use it regularly and 32% irregularly), but growing, acceptance growing
Social Life Cycle Assessment (SLCA)	SLCA is a method for the assessment of the social impact over the life cycle of products and services. Social impacts are classified in stakeholder's categories (workers, local community, society, consumers, and value chain actors) and impact categories. Indicators on LCI level and impact pathways on LCIA level are still being developed. Some indicators and impact assessment pathways were proposed by the Roundtable for Product Social Metrics (reference). SLCA strives to be in line with the ISO 14040 but adapted for consideration of social and socio-economic issues. However, there is no ISO standard on SLCA yet.	UNEP 2009 PRE 2014	Data on social events at company and product level, SHDB	Social	Few users (7% of respondents use it regularly and 20% irregularly); still suffers lack of scientific consensus and definitions, and broader practical implementation, respectively.
Exergy Analysis	Based on the laws of thermodynamics, the exergy analysis describes energy and matter quality and allows evaluating the resource (mass and energy) consumption and resource efficiency for the production of a product.	Szargut 2005 Dewulf et al. 2008	Database with physical and chemical data of the mass	Environment: focus on energy consumption and	Good acceptance in the scientific community and industry but few users because of

	The exergy concept also proves to be of large value when combined with a life cycle approach resulting in an exergetic life cycle assessment (ELCA).		streams, database with exergy values	energy efficiency.	its seeming complexity and lack of benchmarking data (7% of respondents use it regularly and 8% irregularly)
Exergetic Life Cycle Assessment (ELCA)	ELCA is an expansion of an exergy analysis. It combines the exergy analysis with the principles of LCA. ELCA allows quantifying the integral resource consumption on a scientific basis over the whole life cycle of products and services.	Szargut 2005 Dewulf et al. 2008		Environment: focus on energy consumption and energy efficiency.	Good acceptance in the scientific community and industry but very few used (7% of respondents use it regularly and 8% irregularly)
Eco-Efficiency Analysis	The Eco-Efficiency Analysis is a method developed by BASF to quantify the relationship between economic value creation and environmental impact throughout the life cycle of a product or service. Environmental impacts (seven categories such as Land Use, Toxicity Potential) are aggregated into one single environmental damage score and economic data are compiled. Both dimensions are then plotted on a x/y graph.	Saling et al. 2002	Economic data of product/project	Economic and Environment	Few users (high effort required for the assessment), well accepted
Socio-Eco-Efficiency (SEEBALANCE)	SEEBALANCE, developed by BASF allows the assessment not only of environmental impacts and costs but also of the societal impacts of products and processes. The aim is to quantify performance of all three pillars of sustainability with one integrated tool in order to direct - and measure - sustainable development in companies. The ecological data are obtained by performing an LCA according to ISO 14040 and 14044. Similarly, costs are likewise totalled over the life cycle. The societal impacts are grouped into five stakeholder categories: employees, international community, future generations, consumers, and local & national community and indicators summarized in a social footprint.	Saling et al. 2002	Social data at the company level	3 pillars	Few users, well accepted (see above)

	The results can be displayed in a three dimensional graph.				
Product and Organization Environmental Footprint (PEF/OEF)	PEF/OEF methodology aims at being a life cycle-based multi-criteria measure of the environmental performance of products, services, and organizations, developed by the EC. With its approach of “comparability over flexibility”, the PEF/OEF methodology aims at harmonizing existing methods, while decreasing the flexibility provided by the ISO standards regarding methodological choices. This is reflected, for example, in predefined LCIA methods. PEF/OEF methodology is currently widely discussed among stakeholders, and scepticism exists in industry and consumer organizations, as well as in the scientific community.	EC 2013	-	Environmental	Large public debate on EU level, still in pilot phase
Cradle-to-Cradle®	Cradle-to-Cradle® is a design concept developed by Mc Donnough and Braungart based on a holistic economic social and industrial framework that seeks to create efficient and waste free systems. A C2C certification process was implemented based among others on the ABC-X method to assess substances in term of human and eco toxicity (X being not acceptable and A being with low or without risk).	www.epea-hambourg.org www.mbdc.com		Environment, Social	Many users, basic concept accepted
Material and substance flow analysis (MFA and SFA)	MFA and SFA consist in a thorough analysis of the fate of materials or substances within the studied system and are used to calculate performance indicators.	Brunner and Rechberger 2004	Data on material input, stock and outputs	Environment (resource-based analysis)	Well accepted, its use depends on the sector (e.g. often used in the waste and wastewater treatment sectors)
Human health risk assessment	Estimation of the nature and probability of negative impacts on the health of human population exposed to chemicals released by an industrial site/facility.	US EPA guidelines and tools series (http://www.epa.gov/risk_assessment/guidance.htm)	Data on local conditions need to be gathered to	Environment, Social	Well accepted, method quite harmo-

		Sector specific guidances (e.g. European Chemicals Agency 2015)	model pollution dispersion. Data on effect characterization (e.g. inhalation rate, exposure duration, etc.) need to be gathered		nized and mostly applied in a legislative framework
Ecological risk assessment	Estimation of the nature and probability of negative impacts on the ecosystems exposed to chemicals released by an industrial site/facility.	US EPA guidelines and tools series (http://www.epa.gov/risk_assessment/guidance.htm)	Data on local conditions need to be gathered to model pollution dispersion. Depending on the impact considered, data on effect characterization should be gathered	Environment	Few users, lack of framework (No consensus on which impacts should be considered, e.g. impacts on wildlife, vegetation…)
Energy analysis	An energy analysis is the analysis of all the flows going through and stocked within a system. Efficiency indicators are calculated based on the energy balance of the studied system/process. Different types of energy carriers can be considered, e.g. feedstock energy (energy embedded in the input, output and stocked materials) or primary energy. The choice of energy analysis depends on the indicator practitioners want to use in the decision-making process	Data on energy streams	Depends on the type of energy analysis conducted (e.g. primary energy conversion factors, LHV/HHV values of materials, electricity	Environment, focus on energy efficiency	Many users, widely accepted

			production/consumption etc).		
Multi-criteria decision analysis (MCDA)	MCDA includes a collection of formal approaches to decision making which seek to take explicit account of multiple criteria. By utilizing a mathematical procedure they aim to assist decision makers faced with problems that must be considered in terms of multiple, often divergent criteria. Sustainability assessments, by aiming to achieve ecological balance, economic development and social equity, are multi-criteria in nature and so MCDA is becoming increasingly used in this field. There are a range of techniques being used from extremely simplistic to fairly complex models but in almost all cases they assign ranking or scoring to each criteria for each alternative solution , aggregated to provide optimum choices. The most commonly used methods within the field of sustainability assessments are AHP, ELECTRE and PROMETHEE.		Utilizes results obtained using various models and tools earlier in the process. Most models require some 'expert' weighting of different criteria	Economic, environmental and social	Limited use amongst practitioners (13% of respondents use it regularly or occasionally) assumed wider use amongst decision makers

Table 2: Summary of the most established LCIA Methods

LCIA methods	Description	Fundamental documents	Pillar of Sustainability	Acceptance & spread
CML 2001	CML 2001 is LCIA method, which regroups a set of impact categories at a midpoint level: GWP100 (Global Warming Potential 100 years), POCP (Photochemical Ozone Creation Potential), HTPinf (Human Toxicity Potential infinite), AP (Acidification Potential) etc. It contains normalization data for all impact categories at different spatial and temporal levels. The problem oriented midpoint approach consists in a comparison in a common point in the environmental mechanism between emissions and impacts (versus endpoint: a point at the end of the environmental mechanism related to the impact). The spreadsheet containing the different characterization factors and impact categories can be downloaded from the internet via the CML website.	Guinée et al. 2002	Environment	Widely accepted and used (77% of users among respondents from industries and 58% from other sector)
ReCiPe	ReCiPe is LCIA method that uses an environmental mechanism that can be seen as a series of effects creating together a certain level of damage to human health or ecosystem. A set of 18 indicators are used at midpoint level (robust, but not easy to interpret) and 3 indicators at endpoint level: Human Health, Ecosystems and resource availability.	Goedkoop et al. 2009	Environment	Widely accepted and used, more established in non-industrial sectors (23% of users among respondents from industries and 53% from other sector)
USEtox	The USEtoxTM model is an environmental model for characterization of human and ecotoxic impacts in Life Cycle Impact Assessment and for comparative assessment and ranking of chemicals according to their inherent hazard characteristics. Characterization factors are calculated based on the environmental fate, exposure and effects. It was developed by the UNEP and the SETAC.	Rosenbaum et al. 2008 www.usetox.org	Environment, focus on toxicity	Low acceptance in the industrial sector but mostly used and preferred method for assessing toxicity (27% of users among respondents from industries and 47% from other sector)
IPCC 2007	IPCC 2007 is a single issue impact assessment method to assess the global warming potential of product and services, developed by the Intergovernmental Panel on Climate Change. Three different time horizons are available (20, 100 and 500 years). Characterization factors are provided for the direct global warming potential of	Forster, P et al. 2007	Environmental with focus on global warming potential	Widely accepted and used (50% of users among respondents from industries and 42% from other sector)

	air emissions (except for methane), not including indirect formation from nitrogen emissions, carbon monoxide and radiative forcing.			
Impact 2002+	Impact 2002+ is an impact assessment method that proposes a combined midpoint and damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories: Human Health, Ecosystem Quality, Climate Change and Resource s.	Jolliet et al. 2003	Environment	Well accepted, few users, (23% of users among respondents from industries and 32% from other sector)
Ecosystem Damage Potential	EDP is an impact assessment method developed by the ETH Zürich, which characterizes the impacts on land occupation and transformation., taking into account the impact on biodiversity	Frischknecht, et al. 2007	Environment, focus on land use and biodiversity	Well accepted, few users, more established in non-industrial sectors (9% of users among respondents from industries and 26% from other sector)
Ecological Scarcity 2006	Ecological Scarcity 2006 is an impact assessment method following the “distance to target” principle. Eco-factors, expressed as eco-points per unit of pollutant emission or resource extraction, are determined by the current emission situation and by the political targets set by Switzerland or by international policy. It was developed in 1997 and updated in 2006 by the ESU-services Ltd.	Frischknecht, et al. 2006	Environment, only categories for which targets have been set up.	Well accepted, few users, more established in non-industrial sectors (0% of users among respondents from industries and 21% from other sector)

3.2 Summary of the most established LCI databases

In 2011, the joined initiative of United Nations Environment Programme (UNEP) and Society for Environmental Toxicology and Chemistry (SETAC), the Life Cycle Initiative has published a consultation document Global Guidance Principles for Life Cycle Assessment Databases. This work is undertaken within one of the Flagship Activities of Life Cycle Initiative (Flagship 2a “Data and database management”). The focus of this Flagship Activity is on promoting a consistent approach to development of datasets (unit and aggregated), database registry and training. It is aiming to create and coordinate a network of database managers and other closely related stakeholders within ‘data ecosystem’.

Life Cycle Initiative is creating a network of database managers and stakeholders, linking regional groups. It has already received support from Latina American, Chinese, Indian, European and North American regional LCA database expert groups. The aim of this network is to develop and promote the standards for LCA databases.

Between 2004 and 2006, the Life Cycle Initiative developed an LCA database registry. To further maintain and develop it, the platform was moved to GreenDelta (the registry is located at https://nexus.openlca.org).

At the moment two main commercial databases with LCI datasets are commonly used by industry and governmental bodies: GaBi database developed by PE International since 1990s, and ecoinvent database developed by ecoinvent partner institutes and available from 2003. Apart from commercial databases many industries provide their data for free and publish them via European platform on Life Cycle Database (Kühnel and Nickel 2014). These include Alliance for Beverages Cartons and Environment, Association of plastic manufacturers (PlasticsEurope), Confederation of European Waste-to-Energy plants (CEWEP) etc. A full list can be found at the link provided (Kühnel and Nickel 2014).

On the other hand, many companies develop their own databases for their products, which can only be used internally (e.g. Unilever, P&G, Johnson & Johnson, L’Oreal and other companies with own staff being active in LCA modelling).

Apart from that, a number of national life cycle inventory databases have been developed focused on national products, with probably the most developed ones from USA and Latin America.

In 2014, Maki Consulting issued a white paper called “National LCA databases. Status and ways towards interoperability.” with the main goal of providing an overview of national LCA databases worldwide – which ones exist, why and how they have been developed, which content they focus on, how do they deal with interoperability, etc., to derive recommendations for the successful establishment of national LCA databases including their subsequent maintenance and updates; to identify needs for better interoperability of national LCA data and databases.

The EU FP7 project SustainHub (http://www.sustainhub-research.eu) aimed to develop a universal networked data exchange platform. The survey with potential stakeholders was carried out in order to gather the requirements and experiences of industry professionals familiar with challenges of interorganizational data exchange. According to the results of this survey key requirements were identified:

- Capability of the platform to cover various aspects of sustainability data exchange: beyond compliance, labor standards, responsible manufacturing, sustainable use of materials and other aspects of sustainability that are of interest now and may be of interest in the future.
- Comprehensive support of data collection processes as well as automation and support of data preparation: removing the cost burden of collection of data.
- Automation of plausibility checks: missing and low quality data identification and correction.
- Possibilities and opportunities from data analysis: use of datamining tools for more in-depth analysis rather than comparison with a compliance target.
- Full control of outgoing data: data security and protection.

However, the system developed by the project appears to have not received wide adoption, yet.

Another approach that is being developed by a non-for profit association via a web portal www.bonsai.uno is to use computer algorithms for analysis of data submitted by participants in game-like scenarios that ultimately aim to reduce *uncertainty* of the available data for product footprinting. This approach is specifically uncertainty-driven, prioritising the search for new data based on the maximum current uncertainty. The data will be geographically specific. This approach aims to contribute to faster generation of data for ubiquitous LCA and footprinting, and which will complement the more conventional generation of data for databases, such as ecoinvent, for which the data generation process is highly labour-intensive and slow. The engagement of multiple users and use of data analysis algorithms should speed-up generation of the publicly available data. Industrial partners may potentially be interested in using such a platform, since it offers impartiality and independent data quality check.

The following table gives a brief overview of the most established and popular LCI databases (Table 3).

Table 3: Summary of some of available databases of life cycle inventories

Database name	Source	Country	Industry	Cost
Swiss National LCI Database ecoinvent	http://www.ecoinvent.org/	Europe, World	Over 11000 generic LCI datasets covering the following sectors: energy, transport, waste treatment, buildings, chemicals, detergents, graphical papers and agriculture.	commercial
GaBi software database	http://www.gabi-software.com/databases/	World	Offers over 8000 LCI datasets based on primary data collection from companies, associations and public bodies. GaBi databases span industries including agriculture, building & construction, chemicals, consumer goods, energy, metals etc.	commercial
The European Union's European Reference life-cycle Data System ELCD	http://eplca.jrc.ec.europa.eu/	Europe, World	LCI data sets of the European Confederation of Iron and Steel Industries (EUROFER), The Association of Plastics Manufacturers in Europe (PlasticsEurope), The European Federation of Corrugated Board Manufacturers (FEFCO), Groupement Ondulé (GO), and the European Container Board Organisation (ECO) and others (http://eplca.jrc.ec.europa.eu/?page_id=567)	free
Centre for environmental assessment of product and material systems (CPM) LCI database	http://cpmdatabase.cpm.chalmers.se/Start.asp	Sweden	Database contains LCI datasets and LCIA models based on the SPINE data format. Process data represent Activities of households and employers; Agriculture; Air transport; Arts and entertainment activities; Biological; Chemicals and chemical products; Construction; Consumer goods; Crop and animal production, hunting, etc.; Crude oil and natural gas extraction; Energyware; Food products and beverages; Forestry; Fuel; Goods and services for households; Grid electricity and district heat; Land transport; Machinery and equipment; Manufacturing; Materials and components; Metal and mineral mining; Other mining; Paper and paper products; Sea transport; Sector; Transport; Waste handling and processing; and Wood and wooden products excluding furniture.	free
C-Build, C-Food, C-Tex	https://e-licco.cycleco.eu/ https://foodprint.cycleco.eu/ https://spinit.cycleco.eu/auth.php	France	French LCI datasets for building industry, food industry and textile industry.	

LCA food database	http://www.lcafood.dk/	Denmark	Datasets of Danish agriculture provided within the project "Lifecycle Assessment of Basic Food" (2000 to 2003) by the Danish Institute of Agricultural Sciences, Danish Institute for Fisheries Research, Højmarkslaboratoriet, Danish Research Institute of Food Economics, Danish Technological Institute, and 2.-0 LCA Consultants.	free
Base Impacts	http://www.base-impacts.ademe.fr/	France	Dataset of ADEME, the French Environment and Energy Management Agency. It was developed in the framework of the French program for environmental labeling of consumer goods and includes data on a wide range of manufactured products and services: steel, textiles, plastics, electricity, heat etc.	free
USDA National Agricultural Library Digital Commons	http://www.lcacommons.gov/	USA	Food, biofuels, variety of bio-based products in US (corn, cotton, oats, peanuts, rice, soybeans, durum, spring and winter wheat) Irrigation, manure management and farm equipment are under development	free
U.S. Life Cycle Inventory Database	http://www.nrel.gov/lci/	USA, Canada	Commonly used materials, products and processes	free
National Energy Technology Laboratory Unit Process Library	http://www.netl.doe.gov/research/energy-analysis/life-cycle-analysis/unit-process-library	USA	Various aspects of energy production for coal, biomass, NG, nuclear, hydroelectric, wind, geothermal and solar systems.	free
Manufacturing Unit Process life-cycle inventory Heuristics	http://cratel.wichita.edu/uplci/	USA	This site contains raw data and formulas (as heuristics) that can be used to develop transformation unit process data. A life cycle heuristic is to establish representative estimates of the energy and mass loss from a unit process in the context of manufacturing operations for products. The unit process life cycle inventory (uplci) profile is for a high production manufacturing operation, defined as the use of processes that generally have high automation and are at the medium to high throughput production compared to all other machines/equipment that perform a similar operation. This is consistent with the life cycle goal of estimating energy use and mass losses representative of efficient product manufacturing.	free

Canadian Raw Material Database	http://crmd.uwaterloo.ca/	Canada	The Canadian Raw Materials Database (CRMD) is a voluntary project involving a cross-section of Canadian materials industries to develop a database profiling the environmental inputs and outputs associated with the production of Canadian commodity materials. Participants: aluminium, glass, plastics, steel and wood.	free
The Australian Life Cycle Inventory Database Initiative	http://alcas.asn.au/AusLCI/	Australia	The aim of initiative is to provide and maintain a national, publicly-accessible database with easy access to authoritative, comprehensive and transparent environmental information on a wide range of Australian products and services (agriculture, Bio-based materials, chemicals, Electricity, Materials, Transport, Waste treatment) over their entire life cycle.	free

4 Uncertainty and sensitivity

4.1 Introduction

The importance of sensitivity and uncertainty analyses for the interpretation of LCA results has already been highlighted in the late 90s (Huijbregts 1998a). Since then, improvements have been made in this field of LCA and uncertainty analysis is encouraged in several key guidelines such as the ISO standard series and the ILCD handbook. However, such analyses are still rare in LCA studies, mainly because of the lack of a framework to guide practitioners (Finnveden, Hauschild et al. 2009). There is confusion among LCA practitioners on the terminology used to conduct this step of LCA, as the terms sensitivity, variability and uncertainty are often used for one another. For simplification, this document classifies the different terms as follow:

Table 4 Commonly used terms

<table>
<tr><th>Term</th><th>Approach to handle it</th></tr>
<tr><td>Sensitivity: response of output variables and the results to changes made on one input parameter (e.g. amount of emissions) or assumption (e.g. end-of-life scenario).</td><td>Sensitivity analysis: it consists in modifying one parameter or assumption of the model and analysing its impact on the LCA results.</td></tr>
<tr><td>Variability: variation of a parameter depending on the context. Variability cannot be reduced as it is inherent to the system.</td><td rowspan="2">Uncertainty analysis: it consists in taking into account the uncertainty of input data in the calculation of the LCA results.</td></tr>
<tr><td>Uncertainty: lack of knowledge related to one specific input of the system. Uncertainty can be reduced by conducting further research. Uncertainty can be caused by variability.</td></tr>
</table>

4.2 Sources of uncertainty

There are many sources of uncertainty in LCA studies. However, three main sources of uncertainties introduced in LCA models can be defined (Heijungs and Huijbregts 2004, Finnveden, Hauschild et al. 2009):

- Data uncertainty (e.g. temperature of operation of a specific process)
- Methodological choices uncertainty (e.g. chosen LCI modelling framework, i.e. consequential or attributional LCA; chosen time horizon)
- Model uncertainties (e.g. the assumed linearity between emissions and environmental impacts or the model behind characterization factors calculation).

Data uncertainty can be caused by several factors such as the uncertainty related to measurement tools or the consideration of non-specific processes but also by data variability (e.g. the heat consumed in a process at a specific place around the world might not be the same at another place for the exact same process, but one value should be chosen in the model, which introduces uncertainty in the results). Most methodological studies on how to improve the consideration of uncertainty in LCA focus on data uncertainty and most practitioners consider data uncertainty rather than methodological choices and model uncertainties in their studies.

4.3 Methodologies to handle data uncertainty in LCA

4.3.1 Quantification of data uncertainty

Three main approaches are followed by practitioners to deal with data uncertainty:

- Scenario analysis: when a parameter is unknown despite the fact that all the necessary research has been done, practitioners often conduct scenarios analysis. The LCA results are calculated using different parameter values or different assumptions. For example, if the end-of-life of a material is unknown, the results can be calculated considering first incineration as an end-of-life scenario and landfilling as a second scenario. Scenario analysis is based on the choice of discrete values.
- The Pedigree Matrix: Pedigree Matrix is used when uncertainty of input data is unknown. It consists in estimating data quality level based on experts or practitioner judgment. The quality criteria (e.g. completeness) are related to indicator scores. Then, an uncertainty factor is assigned to each of these indicators scores. The Pedigree matrix determines the distribution of input data assuming a lognormal distribution.
- Statistical analysis: different statistical analyses of data are used by practitioners. The most common one is based on the classical statistical theory and consists in assigning a probability function to each parameter. These probability functions (e.g. uniform, lognormal, normal triangular etc.) can be determined when a large number of values are available for a given parameter or based on expert judgment. If such a probability function cannot be determined, another approach can be followed, based on the possibility theory, which consists in representing parameters uncertainty using fuzzy intervals.

Other non-conventional approaches can be found in scientific literature, e.g. based on Bayesian analysis or non-parametric statistics(Finnveden, Hauschild et al. 2009).

4.3.2 Propagation of data uncertainty and uncertainty of the LCA results

The main technique used to propagate uncertainty to the LCA results is the Monte-Carlo analysis (Groen, Heijungs et al. 2014), which consists in randomly sampling values for each parameter based on the probability function, calculating the results based on the sampled values, and repeating the operation multiple times to define the probability function of the LCA results. Today, most LCA software tools allow performing Monte-Carlo analyses.

Other uncertainty propagation techniques can be used, but their practical implementation by practitioners is today very limited. Several variations of Monte-Carlo sampling technique such as the Latin hypercube sampling and the quasi Monte-Carlo sampling are found in the scientific literature (Groen, Heijungs et al. 2014). Another approach, the analytical uncertainty propagation, can be used when limited information on parameters is available, as it aims at calculating the variance of the results based on the variance of the input parameters. Therefore, the probability functions of the input parameters do not need to be defined. The propagation of the uncertainty defined by fuzzy intervals is very similar to Monte-Carlo analysis but consists in randomly sampling intervals instead of single values (Clavreul, Guyonnet et al. 2013). Today, the implementation of these propagation techniques is not possible through classical LCA software tools. Therefore, practitioners need to use modelling software tools such as MATLAB to conduct the analysis.

4.4 Methodologies to handle methodological choices and model uncertainties in LCA

The uncertainty related to methodological choices is rarely considered in LCA studies. However, it is recognized that methodological choices such as the chosen time horizon (Guo and Murphy 2012), LCI modelling framework (Thomassen, Dalgaard et al. 2008) or allocation methods (Luo, van der Voet et al. 2009) can modify the conclusions of a study and should be given more attention. For some methodological choices, an analysis of uncertainty is not always necessary, as uncertainty can be reduced by a better adaptation of the methodological choice to the context of the study. For example, the uncertainty introduced by the choice of the LCI modelling framework could be most of the time reduced by better adapting this choice to the goal of the study (Thomassen, Dalgaard et al. 2008). Indeed, attributional and consequential LCA studies do not aim at answering the same question: attributional LCA aims at identifying the environmental burdens associated with a product or service, whereas consequential LCA aims at identifying the environmental consequences of a product or service on other sectors. Today, practitioners do not pay enough attention to this choice and should better justify it. For other methodological choices, conclusions should not be drawn only based on one approach and different approaches should be tested before drawing any conclusion on the results. For example, the LCA results can be calculated with different time horizons, e.g. 50, 100 or 500 years (Thomassen, Dalgaard et al. 2008, Basset-Mens, Kelliher et al. 2009), or different allocation factors can be tested, e.g. energy or mass allocation (Luo, van der Voet et al. 2009).

The uncertainty introduced by the LCA model is even more rarely considered by LCA practitioners. Few examples can however be mentioned. First, some authors aim at reducing the uncertainty related to the LCA model, e.g. by testing the use of time-dependant freshwater ecotoxicity characterization factors for metal emissions (Lebailly, Levasseur et al. 2014). In general, model uncertainty can be reduced by improving LCA models, especially the characterization of environmental impacts. Secondly, some authors aim at quantifying the uncertainty of the LCA models, e.g. by conducting a Monte-Carlo analysis on characterization factors for GHGs using probability functions (Lo, Ma et al. 2005) or studying how emissions fate and transport models can be affected by the variation of LCA input data (Mayo, Collier et al. 2014). However, this field of research is still limited.

4.5 Challenges associated with uncertainty handling in LCA

4.5.1 Decreasing complexity of uncertainty analysis complexity while maintaining the accuracy of LCA results

Uncertainty analysis is resource and time consuming. Therefore, it is acknowledged that it needs simplification to be more widely applied by practitioners.

Several studies showed that few parameters are often responsible for the overall uncertainty of the LCA results (de Koning, Schowanek et al. 2010, De Soete, Debaveye et al. 2014). Therefore, in practice, uncertainty analysis based on the quantification of the uncertainty of few parameters is in general enough to estimate the overall results uncertainty. To identify them, a pre-selection of parameters based on a sensitivity analysis can be conducted (Huijbregts 1998b, de Koning, Schowanek et al. 2010, Clavreul, Guyonnet et al. 2012). This approach is the most used method to select parameters but is still not commonly followed by practitioners today. In most cases, practitioners conduct sensitivity analysis manually. Note that the CMLCA software allows conducting sensitivity analysis based on the 1st order Taylor expansion method (Heijungs 2010).

Moreover, the uncertainty of LCA results highly depends on the model complexity as complex models tend to better model the real system than simple models. However, complex models require taking more parameters into account, thus increasing the uncertainty related to parameter values (van Zelm and Huijbregts 2013). Therefore, trade-offs exist between model and parameter uncertainties, and an optimal model complexity to lower the overall uncertainty of the LCA results should be identified. However, the optimal model is specific to each case and work should be carried out in every sector to give insights to practitioners on possible model simplifications. Note that such a work has been done in the case of pharmaceuticals synthesis processes (De Soete, Debaveye et al. 2014).

4.5.2 Improving the practical implementation of uncertainty analysis

Most of the techniques used to propagate uncertainty to the LCA outcomes require the use of complex statistical modelling and specific software tools that are not necessarily accessible for LCA practitioners. Today, the Monte-Carlo uncertainty propagation method is the only one widely used by LCA practitioners because of existing software tools allowing such analysis. The implementation of more accurate uncertainty analysis techniques (e.g. considering both probability and possibility theories when different levels of information are available for different parameters (Clavreul, Guyonnet et al. 2012)) requires the development of supporting software tools.

One major issue when practitioners conduct an uncertainty analysis concerns the probability functions assigned to each key parameter. Indeed, it often happens that probability functions associated with the studied parameters are unknown. Therefore, practitioners often choose a distribution without basing their choice on solid statistic estimations. This is one of the main drawbacks of the Pedigree matrix, which is based on the assumption that all input variables have a lognormal distribution. To improve the choice of probability functions, practitioners can involve experts in the field of their study. Moreover, information on commonly considered parameters and their probability functions could be gathered for different sectors. Such information would require an intensive data collection process within these sectors, as a large number of data is necessary to estimate the probability function of the chosen parameters. However, such a project would help increasing the accuracy of uncertainty analyses in LCA studies.

4.5.3 Dealing with uncertain results in the decision-making process

Uncertainty analysis plays a significant role in the consideration of LCA results in the decision-making process. Indeed, some decision-makers do not account for LCA results in process because of the non-accuracy of the results or the fact that uncertainty is ignored. On the other hand, some decision-makers do not take into account LCA results because the calculated uncertainty is too high. Therefore, a balance is necessary to make uncertain LCA results usable by decision-makers.

One way of increasing the consideration of LCA results by decision-makers is to increase the communication between LCA practitioners and the decision-makers on the future use of the results. Indeed, sometimes LCA studies are not conducted to exactly answer the question of decision-makers, which conducts to increase the uncertainty of the impact of the decision itself. An *ex ante* (i.e. before the LCA study is conducted) methodology based on the evaluation of the uncertainty of the results depending of the type of LCA study was proposed by Herrmann et al. (Herrmann, Hauschild et al. 2014). The authors proposed an LCA classification matrix to help decision-makers identifying and communicating to LCA practitioners the type of LCA study they need to take the decision. Thus, the aim of this approach is to help practitioners and decision-makers better communicating between each other on the suitability of an LCA study type to answer a specific question with the lowest uncertainty.

4.6 Conclusion

A lot of progress has been made during the last decades on how to consider uncertainty in LCA studies. However, it is still rarely performed and even if accurate methods have been tested by the scientific community to assess and propagate uncertainty, practitioners rarely follow a consistent and complete approach. This is mainly due to a lack of framework, the fact that uncertainty analysis is a time and resource consuming step and since tools to implement complete uncertainty analysis are not always accessible for practitioners. Therefore, research projects should be encouraged to:

- Define a clear framework to conduct a step by step uncertainty analysis
- Identify for every sector or product groups key parameters on which LCA results mainly depend and for which uncertainty should be thoroughly calculated
- Integrate supporting features to conduct uncertainty analysis in LCA software tools

5 Integration of LCA and ERP tools

In many large corporations management of data across the organisational structure (production, planning, finance, legal, procurement, human resources, EHS, quality, engineering, validation, marketing, board, etc.) is done within custom-build IT systems called Enterprise Resource Planning (ERP). The tasks of such systems largely fall into four application areas: business intelligence, enterprise management, commercial applications and customised ERPs or their modules. As an example of the more straightforward implementation of an ERP is manufacturing resource planning system (MRP) that regulates production based on stock levels and orders supplies based on in-house stock levels. The data management capability of an ERP is highly attractive for applications in resource-based sustainability assessment, since access to high quality data for building life cycle inventories is the most important barrier for ubiquitous use of LCA methods.

The challenges of using ERPs for sustainability assessment are discussed in the recent research paper (De Soete 2016). One of the technical issues that may exist in the already operating ERPs is the ability to access to the required for sustainability assessment data. The shop-floor sensors and logging systems, supervisory control and data acquisition systems are separated from the business departments by a manufacturing execution system (MES). The raw material and energy flows data, product quality measurements data that would allow evaluation of indicators for sustainability assessment, may not penetrate through MES. When such data is available, another unresolved technical problem is the consistency of the data, for example the lack of standardisation on units of physical measures to be used. The importance of the issue of data standards is difficult to overestimate. Lack of standards for data exchange is apparent in the way how different tools are used by sustainability assessment experts. It is not straightforward to exchange life cycle inventories between different databases or even between commercial suppliers of LCIs, and different LCA commercial tools, such as GaBi, Umberto, Simapro, OpenLCA, etc. Some converting tools have been developed, but are a cumbersome work-around and invariably introduce errors requiring manual correction. Further useful tools such as communication between process flowsheet models and life cycle inventories have not been developed as commercial realisations at all. Once access to and standardization of data is resolved within a single enterprise, the next important challenge is access to data along the supply chain. This is critical for evaluation of sustainability metrics and for correct allocation of burdens. However, transparency of data along the supply chain will meet significant challenges, such as the balance between the need for data and social responsibility and commercial sensitivity of the data. Solution may lie in the use of aggregated data or ‘black box’ data models, which preserve business integrity, whilst enabling data exchange. The use of averaged market data also avoids commercial sensitivity, but this introduces significant uncertainty into LCAs. Another problem related to supply chain is its reliability. Unforeseen events introduce disruptions that are impossible to predict. Within this context, resilience of business and technology systems under climate change is the topic of many on-going research projects. In critical industry sectors the issue of supply chain reliability is a matter of regulation, such as Good Supply Practices of pharmaceuticals. In other sectors downstream users employ the tactics of using multiple suppliers to ensure reliability of supply.

Recent academic study proposes a general framework of integration of data available within ERPs into sustainability assessment, see Figure 2. In this concept corporate sustainability reporting and evaluation of product sustainability is facilitated by access to data in an ERP system equipped with a module customised for LCA. This module requires access to LCI and methods of evaluation of life cycle impacts. The inputs into life cycle models are delivered through MES, which pulls the required data from its own models and reports, as well as from the plant floor system: sensors, control system, etc.

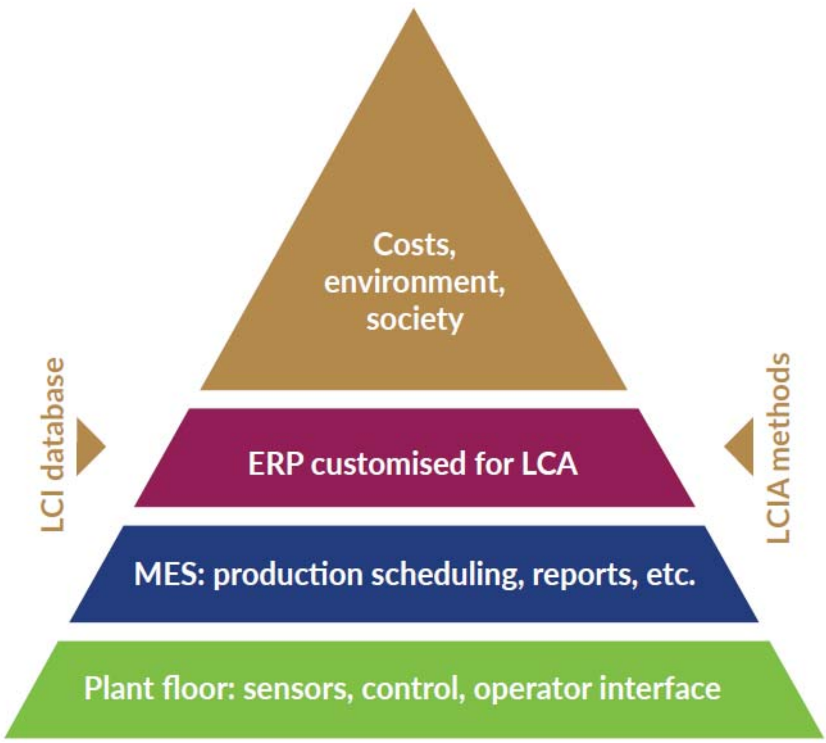

Figure 2: The concept of a general framework for integrated product and organisational sustainability. Adapted from (De Soete 2016).

6 LCA for multi-criteria decision making

6.1 Overview

Multi-criteria decision methods (MCDM) cover a range of methods and tools that aim to assist groups or individual decision makers to more fully explore the decisions they are making. This is achieved through formal, structured and transparent processes for considering complex decisions based on multiple criteria. It should be noted that MCDM does not aim to provide the 'right' answer, nor does it provide an objective analysis and it does not relieve decision makers of the responsibility of making difficult judgments. Rather, MCDM aims to assist the decision maker in feeling comfortable and confident in the decision made by (Belton and Stewart 2002):

- Enabling decision makers to gain a better understanding of the problem faced,
- Organising and synthesising the entire range of information,
- Integrating objective measurements with value judgements,
- Making explicit and managing the decision maker's subjectivity, and
- Ensuring that all criteria and decision factors have been taken properly into account.

In this way, MCDM can lead to a more considered, justifiable and explainable decision, whereby the analysis provides an audit trail for the decision. Bolton and Stewart (Belton and Stewart 2002) state that subjectivity will be inherent in all decision making, from the choice of criteria that the decision maker is using to the relative importance placed on those different criteria, but by using a structured and transparent aid to decision making those subjectivities can be made explicit and clear.

One of the key drivers for performing MCDM is that in complex decision making undertaken without a structured and transparent process there is often an inevitable simplification of the decision. Without a systematic decision process a larger number, of perhaps individually less important, indicators may get ignored in the final decision although their influence all together may be remarkable. Such a simplification would rely too heavily on a small number of key criteria. Equally, unstructured decision making often fails to make use of or consider the scale and context within the whole system or the uncertainty surrounding different criteria. Due to its relatively simple methodology, MCDM can be easily used in conjunction with Monte Carlo simulation to take account of modelled uncertainty of the criteria values, uncertainty of the subjective criteria preferences and provide a known level of certainty in the proposed decision, unachievable in unstructured decision-making.

As stated above, MCDM can be considered an umbrella term for a range of tools and methodologies that largely follow the processes outlined. The level of complexity, interaction with the decision maker and level of detail utilised in the decision-making process can vary substantially. In general the decision maker follows the same process:

- Identify multiple criteria on which to base their decision,
- Identify multiple alternative solutions to their decision,
- Provide (subjective) ranking or weighting of criteria, and
- Provide values, rankings or weighting of alternatives for each criteria.

Through a series of mathematical processes, the result of the MCDM will be a ranking of the alternative solutions, in some cases alongside scores to provide additional differentiation of alternative solutions. These rankings or scores remain subjective and relate specifically to the decision maker's (or group's) stated preferences.

6.2 Use of MCDM in sustainability assessment

By definition, sustainability assessments involve a number of different and often disparate criteria to be considered, aiming to achieve ecological balance, economic development and social equity. It is therefore inevitable that a sustainability assessment of a product, process or activity will necessarily be multi-criteria based and that those economic, environmental and social criteria can be contradictory. For these reasons, a number of studies have incorporated a variety of MCDM techniques into sustainability assessments across a range of industrial sectors. In addition a number of studies have considered and compared a range of MCDM methods applied to sustainable development (Azapagic and Perdan 2005a, Azapagic and Perdan 2005b), sustainability assessment (Cinelli, Coles et al. 2014) and LCA studies (Benetto and Dujet 2003). These studies have identified value- or utility-based approaches and outranking approaches, specifically Analytical Hierarchy Process (AHP), Multi-Attribute Utility Theory (MAUT), Elimination Et Choix Traduisant la Realité (ELECTRE) and Preference Ranking Organisation Method for Enriched Evaluation (PROMETHEE) as the most commonly used within their areas of study.

AHP and MAUT are value or utility based MCDM approaches. Within these approaches to MCDM each alternative for each criterion is first scored. Then the scores for the alternatives are aggregated across all the criteria to provide an overall score for each alternative and thereby provide a ranking. AHP is the most commonly used MCDM method with a very wide range of software tools available to aid the process. Unusual to the other common MCDM techniques AHP does not make direct use of actual numerical values for each criterion and alternative, rather it elicits subjective pairwise preferences from the decision maker to determine both criteria importance and relative scores of each alternative within each criterion.

PROMETHEE and ELECTRE are two outranking approaches to MCDM. Rather than calculate scores for each alternative, they determine outranking relationships between alternatives and in doing so calculate a final ranking. ELECTRE has been frequently used in the past, especially across Europe but due to a wider range of software and graphical enhancements, PROMETHEE is becoming increasingly commonly used as highlighted by Cinelli et al. (Cinelli, Coles et al. 2014).

For more detailed information about MCDA in innovation projects see the MEASURE **background document** “Towards sustainability in SPIRE innovation projects”.

7 Presentation and communication of LC(S)A results

Due to the complexity and uncertainty of the underlying models, the communication of LC(S)A results at different levels (e.g. research and development teams, decision makers on business management level, consumers, certification bodies) is a challenging task. A balance has to be found between the transparency of complex results and a pragmatic way to communicate comprehensive results. Best practice standards for communication and translation into meaningful messages of sustainability issues (internal and external) would help to further improve the understanding and the broader acceptance of its value as well as limits.

Communication of LCA results in an industrial environment has so far been found to take place internally and in academic or B2B settings. In such situations, the focus is usually on the most relevant or prominent indicators and uncertainty is generally taken into account but not quantified or graphically represented. Relative comparisons between alternatives are favoured in order to have a reference point, and to reduce the effect of uncertainty due to input data. Communication of LCA outcomes to consumers (B2C) is only in its infancy, and has been explored more systematically in the framework of several types of footprints such as the French Grenelle Law consumer goods labelling experimentation, and currently in the framework of the EU PEF Pilot. An exception to this is the automotive industry that actively communicates LCA results to their fleet customers. The customers are business as well as end-consumers who actually use the product.

No uniform or one-size-fits-all solution has been identified so far, but some approaches seem to work better than others. In the following paragraphs, some typical types of LCA data presentation in B2B communication are highlighted.

The type of communication depends on the target audience and on the goal of the LCA: Few types of results representation can be distinguished:

- An absolute representation of the environmental impact of a product (cradle-to-gate) will provide information about the main contributors and possible room for optimization (Figure 3a). Nevertheless, it will not give the information about how good the product is compared to a baseline (competitive product for example) or if an optimization of the process parameters would finally impact the overall life cycle significantly (i.e. for products for which the use phase has the overall biggest impact).

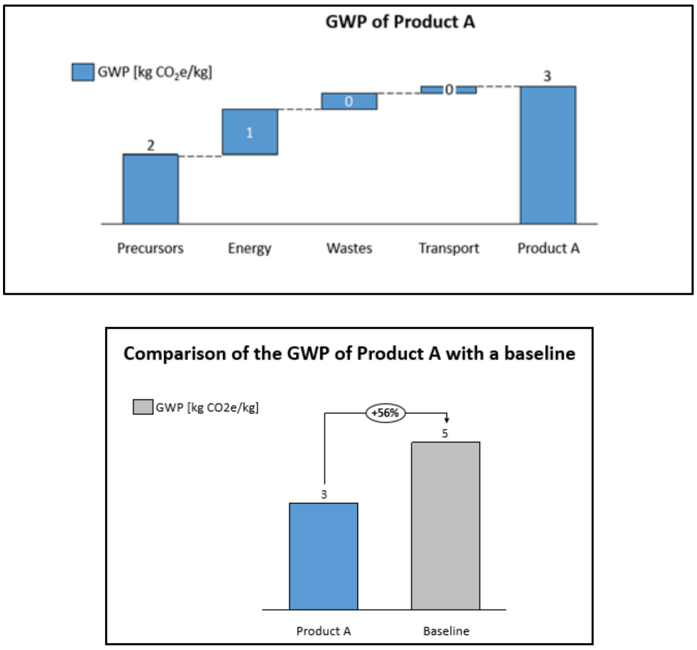

Figure 3: Example of a) absolute representation (up) and b) relative representation of results (down).

- A relative representation of the impact of a product versus a baseline is a better way to interpret a result and to use the results for decision-making easier (Figure 3b). Nevertheless, the difficulty remains in choosing the suitable baseline and using the same parameters and background conditions for both systems in order to have comparability.

There are several possibilities to express the results of a LCA:

- In kg CO_2e/kg for GWP, for example, or kg Ethene equivalent for POCP that is useful for communication between LCA experts, but might not be suitable when communicating with marketing departments or other non-LCA experts. Consequently, a translation in another unit is sometimes required (euros/kg or km/kg according to the field of specialization or the goal of the analysis) especially when both sides do not have the same knowledge (Figure 4).

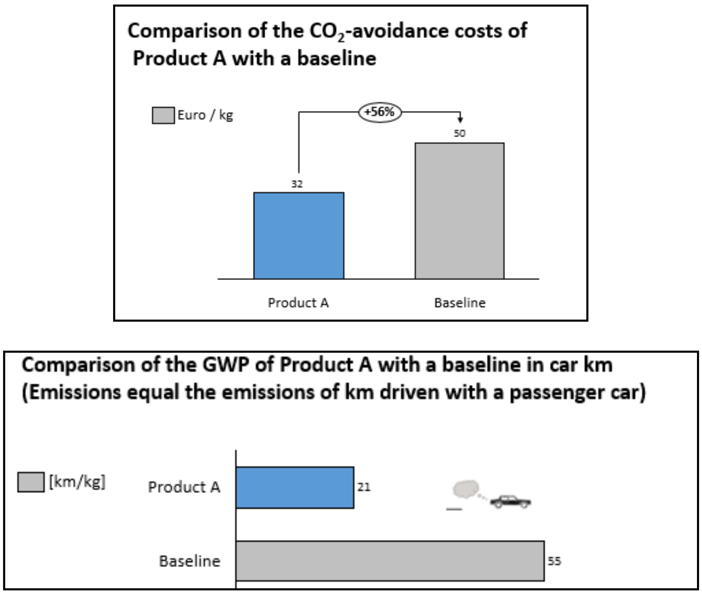

Figure 4: Examples of a) relative representations of results transferred in monetary terms (up) and b) in km/kg in the case of GHG emissions of a passenger car (down).

- Representing normalized indicators to compare the overall impact of products (Figure 5):

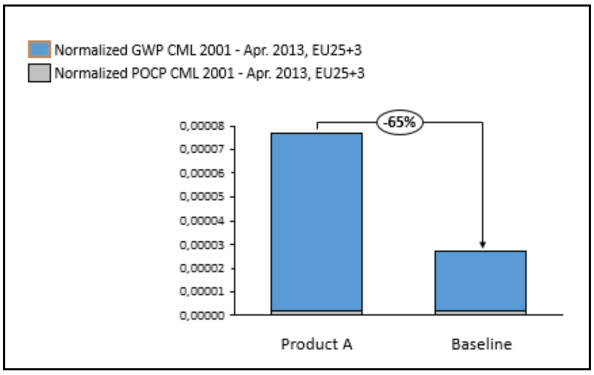

Figure 5: Example of a normalized method: normalization with the respective European emissions (of 28 European countries) for each indicator (Sleeswijk, van Oers et al. 2008).

Communication based on one single indicator is a pragmatic approach but does not give a full picture on the environmental performance and important information might be neglected. Additionally, the acceptance of presenting aggregated or even single score results (end-points) is low in the LCM community. These kinds of aggregations and/or normalization approaches have the advantage to be easy to understand at first sight, but the risk of information losses are high. They are also criticized as being not enough transparent. The overall result might be easy to interpret but the difficulty remains in the understanding of the calculation approach and underlying information.

Nevertheless, graphics based on several indicators (Figure 6) might be very difficult to interpret and lead to misunderstanding for non-LCA experts. The complexity is moreover getting higher with the number of indicators represented and a simple overall statement cannot be made.

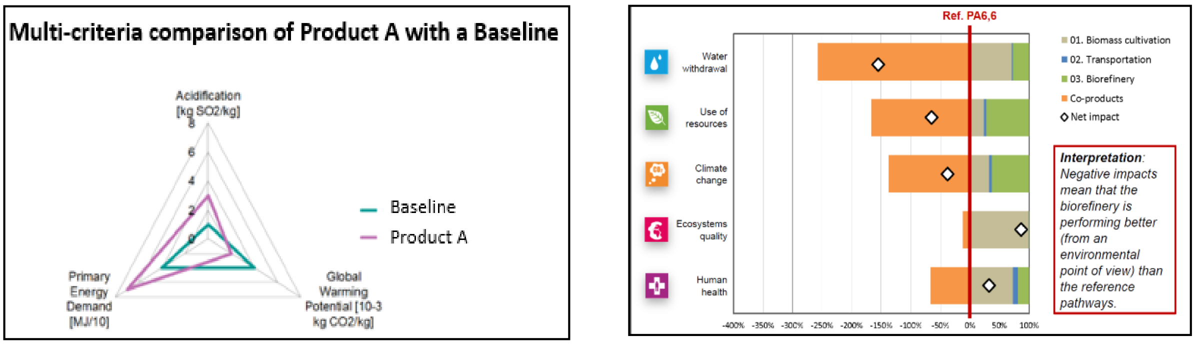

Figure 6: Examples of results representation based on several indicators (Sun, Wei et al. 2014).

There is currently no general agreement in the LCM community which communication methods to use, but there is a general understanding that:

- In case of a high uncertainty of the results (e.g. due to the allocation approach, assumptions), the range of results should be communicated to have a more-informed decision-making at least for B2B communication, even if it makes the complexity higher.
- Simple visuals and a translation of LCA results into directional guidance that engages consumers is favoured in B2C communication. Focus is given on selected, most relevant indicators that steer towards the right behaviour. Examples of sector A B2C communications are e.g. recommendations for cold laundry washing (“Turn to 30”) or to the use of compact products that have less packaging waste per use.

Compared to sector A or B, the solid waste management (SWM) sector[2] has the specificity that results are not communicated on a B2B or B2C basis. Indeed, sustainability assessment studies are most of the time conducted for internal purposes or for public authorities in the framework of waste management planning. In sustainability assessment studies of a product, results can be communicated using relative representation, i.e. by comparing the results with the results of a benchmark product. In the SWM sector, the comparison with a “benchmark system” or “benchmark technology” is not possible, as results not only depend on the assumptions made during the assessment, but also on local conditions. Therefore, a baseline scenario for which a full assessment is made replaces the benchmark product used in product assessment studies.

[2] In order to follow the project findings in the three observed sectors, please refer to the respective background documents

Results can also be communicated to a wider public, e.g., in the framework of a MCDA for which stakeholders (residents, municipalities etc.) are asked to rank different waste management options based on several indicators. In this case, an issue can be that results are presented to the different stakeholders without giving them the opportunity to check the validity of these results (Hanan, Burnley et al. 2013). Public consultation to choose the most sustainable waste management option is not much developed yet. However, in the SWM sector, the involvement of stakeholders who do not have a scientific, economic or social background is increasing, and methods to communicate comprehensive results to this new public should be found.

8 Product Environmental Footprint

8.1 Introduction

In 2008, the European Commission (EC) published its *Action Plan on Sustainable Consumption and Production* (SCP/SIP), including various proposals for a number of tools such as: Ecolabel, Energy Label, Ecodesign, Retail Forum, and others. The launch by the EC of the Resource Efficiency Roadmap followed in September 2011; the communication on "*Building the Single Market for Green Products (SMGP) - Facilitating better information on the environmental performance of products and organizations"* was released on 9 April 2013. The recent publication of the Resource Efficiency Roadmap has further strengthened and defined the future role of the environmental footprint methodology by explaining that the Commission will:

- Establish a common methodological approach to enable Member States and the private sector to assess, display and benchmark the environmental performance of products, services and companies based on a comprehensive assessment of environmental impacts over the life-cycle ("environmental footprint") (in 2012);
- Ensure better understanding of consumer behaviour and provide better information on the environmental footprints of products, including preventing the use of misleading claims, and refining eco-labelling schemes (in 2012).

The European Commission's DG Environment, working closely with its in-house science centre DG Joint Research Centre (JRC), has developed two methods to measure the environmental performance throughout the life cycle, the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF). The methodologies are based on the LCA method and the International Reference Life Cycle Data System (ILCD) handbook as well as other existing standards and guidance documents, including ISO 14040/44, ISO/TS 14067, ISO 14020, PAS 2050, BP X30-323, WRI/ WBCSD GHG Protocol.

The aim of PEF is to develop a harmonized methodology for calculation of the environmental footprint of products. A reliable, credible and consistent measure of this environment footprint is a fundamental step in raising business and consumer awareness of potential impacts, thereby helping to reduce that footprint. In order to achieve this, rules have to be developed for individual product categories to allow consideration of specific product-level details.

In this regard, some 25 pilot projects are currently running from 2013 to 2016 to develop so-called Product Environmental Footprint Category Rules (PEFCRs) per sector (EC 2013a). The overall methodological framework is given by the PEF Guidance (EC 2013b).

8.2 Relationship between PEF and the MEASURE Roadmap

First and foremost, the EU PEF initiative has no direct or formal link with the objectives of SPIRE. Nevertheless, both initiatives share the vision of reducing – mid to long term – the emissions from (process) industries, either directly at the processing/manufacturing plant, or in the supply chain via customers and consumers who may pick the products with a lower life cycle impact. It is therefore important that final guidelines ("roadmaps") or legislation resulting from both endeavours are at least directionally similar and/or complementary.

Another potential link at least for the European process industry companies is OEF, which builds on similar life cycle oriented methodologies as the PEF. OEF is however not product, technology or project oriented and therefore out of the SPIRE scope.

Within the EU PEF initiative, the development of PEFCRs for specific product categories can be a relevant aspect for MEASURE as well, since the Category Rules aim at describing in a very detailed and prescriptive way which/how life cycle-based tools should be applied. The final objective of PEF is to provide and communicate factual environmental information to the consumer (B2C), or to other partners in the supply chain (B2B). In order to avoid non-verifiable information, false competition and/or green washing, the PEFCRs tend to be defined in a narrow and prescriptive way.

The PEF Guidance may not necessarily apply for other uses of LCA and life cycle tools within industry (e.g. internal use in R&D), but it will certainly put a strong mark on what is considered 'good practice' and 'good data'. In that sense, it can be useful to compare the to-be developed MEASURE Roadmap next to the PEF approach and Guidance (as far as this is defined and understood today).

The following Table 5 summarizes the important aspects when comparing the SPIRE/MEASURE requirements and the perceived PEF objectives:

Table 5 Comparison of SPIRE/MEASURE with PEF objectives

	SPIRE / MEASURE	Perceived EU PEF focus (as of Sept. 2015)
Goal and Scope	Evaluate R&D ideas and proposals regarding sustainability for company internal decision making as well as SPIRE project and application assessment	1. Provision of consumer information by assessment of environmental footprint of end consumer products and ranking within PEFCR in comparative way to drive improvement 2. streamlining environmental labelling schemes in EU
Target audience	Decision makers within companies, innovation managers and EU SPIRE call reviewers, including SMEs	Mainly end consumers, B2B only indirectly
Raw data uncertainty	High due to incomplete or estimated mass and energy balances, especially in early stage of innovation	Rather low for established products (primary data); higher for secondary data of supply chain and use phase
Connectivity need for process design software and LCA software as well as need for automated calculation procedures	High to enable efficient procedures in process development and optimization due to many different scenarios and parameter variations to be checked in development phase	Lower – assessment of final products will remain expert task only
Need for streamlined and simplified tools to allow wider use in industry	Very high – assessment must be possible vastly without expert involvement in R&D departments, especially in early project stages where hundreds of ideas are screened per year	In general lower – only final B2C product will be assessed, probably by experts
Value chain position of process industries	Mainly early and B2B business (except consumer goods)	Mainly B2C
Importance of external communication aspects	Low – R&D evaluation and assessment are mainly internal processes in industry; higher within SPIRE projects	High – B2C requires vast communication efforts, e.g. by green product labelling
Need to streamline with ISO 14040 and 14044	Low – as simplified tools are necessary in R&D	High due to current practice in companies; many European process industry companies are multinationals, i.e. globally applicable standards are preferred (e.g. they also prefer ISO14000 compared to EMAS for site environmental management)
Comparative character of study (for author)	High – in R&D new ideas and processes always need to be benchmarked against suitable alternative / current practice, etc.	Only if PEFCRs will define benchmarks

Used impact categories and indicators	Reduced set of reliable and lead-indicators is normally sufficient normally in process industry (e.g. GWP, EP, AP, PED)	Comprehensive
Need for publicly accepted specific PEFCRs to ensure comparability and detailed guidance	Lower for company internal assessments of R&D projects; however potentially helpful if existing	High if comparative labelling is the objective

8.3 Potential impact of PEF requirements for LCA practice in industry

Since it is quite likely that the EU PEF initiative will – in one form or another – impact the direction of environmental information/labelling at the product and brand level, the participants in PEF pilot projects are interested to explore the likely implications of such an approach. At the time of writing, the PEF pilots are only halfway, and it would be premature to draw any firm conclusions. Nevertheless, a few observations can be made: PEF applies to established products on the market, therefore simplified life cycle methodologies are not needed/appropriate

- PEF does not take into consideration neither social, nor cost aspects.
- PEF, if imposed into policy, will drive harmonization of LCA practice in a sector due to the need for (competing) companies and other stakeholders to collaborate on category rules. The PEF will foster collaborations across the value chain.
- PEF has very strict data quality requirements, which at present cannot be fully met by the data commonly used in most sectors. Generation of new, better, data is generally a slow process that may be constrained by many external factors (see also sectorial reports in D3.1, D3.2 and D3.3).
- PEF will encourage the generation of primary (producer-specific) LCI data, in order to allow better product-differentiation.
- Some of the indicators proposed as mandatory (e.g. ecotoxicity with USEtox method, water use, land use) are contested by industry as being still immature for public deployment (see separate discussion of USEtox issues in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**).
- By defining Product Category Rules, the PEF is increasing the comparability of LCA studies for a given category, thereby reducing uncertainty ranges around the calculated results. This may bring quantitative product comparisons within reach, at least for some indicators.
- The benefit of the PEF versus other (voluntary) sectorial Life Cycle Management tools (e.g. AISE Charter for Sustainable Cleaning) in terms of driving environmental improvements across a whole sector is not evident yet. Other approaches

may be equally or more impactful for the market with less administration and burden for the sector.

- PEF will revive the debate on single indicators and (value judgment based) weighting in LCA.
- The PEF may become something specific to the EU, as e.g. the US-EPA is exploring very different (more integrated) metrics and measures for sustainability assessment. This can be problematic or creating complexity for globally operating companies.

8.4 PEF compatibility with current ISO standards and ecolabels

Based on midterm results of the pilot phase, the following (methodological) issues are noted:

- The current PEF approach does not fully conform to relevant international standards like ISO 14025, ISO 14040 and ISO 14044. Nevertheless, ISO-compliant terminology could be used without any negative consequences on the technical outcome of the PEFCRs.
- The product categorization with CPA/NACE-codes does not have sufficient granularity to cluster “comparable” product categories.
- PEFCRs will be newly developed for product categories with already existing PCRs (i.e. EPDs) and therefore add to proliferation and multiple reporting schemes for companies and SMEs, which is opposed to the harmonization objective.
- The newly developed PEFCRs do not necessarily represent a significant improvement over existing PCRs based on existing international standards. There are formal differences, but the scientific or technical quality is not necessarily higher.
- The variability in the real world cannot be easily transferred into fixed modelling approaches or a representative product. Whether the desired level of calculation reproducibility and (brand) comparability will be achieved is still a question mark.
- The restriction of applying cut-off criteria leads to inconsistent and asymmetric system boundaries.
- PEFCRs from the different pilots suffer from huge inconsistency between each other with regards to almost all aspects of LCA, be it the system boundaries, the functional units (‘unit of analysis’), representative products or data, how relevant impact methods are selected and used, approach to weighting, etc..
- The selection of data sources will lead to bias in the PEF screening studies. This is highly visible in e.g. the ecotoxicity impact methodology.

Overall, these and other issues are widely discussed into several publications (Finkbeiner 2014, Galatola and Pant 2014, Lehmann, Bach et al. 2015, Manfredi, Allacker et al. 2015) , as well as in a position paper of The German Ministry of Environment, Nature Conservation, Building and Nuclear Safety and The German Federal Environment Agency (TUB 2014), endorsed by the German Industry Association (BDI 2015).

8.5 Conclusion

The EU PEF project has no direct or formal link with the objectives of SPIRE. Nevertheless, both initiatives aim to impact LCA adoption and *modus operandi*. The EC promotes the use of PEF for measuring and communicating (B2B and B2C) environmental lifecycle performance of products and organizations. Thus, it provides opportunities to support decision-making processes at all levels, that is, industry, policy and society. However, for this, information obtained must be based on a solid methodology, and appropriate communication tools must be used. Both of these conditions are not yet ensured. It is, however, acknowledged that the PEF process is still at pilot stage. In order to promote harmonization in future, also globally, PEF has to be based on solid internationally agreed references, in contrast to the current version that may lead to further proliferation and segmentation, but not harmonization.

9 Abbreviations

AP	Acidification Potential
ADP	Abiotic Depletion Potential
B2B	Business-to-Business
B2C	Business-to-Consumer
CED	Cumulative Energy Demand
ELCD	European reference Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
EPD	Environment Product Declaration
ERP	Enterprise Resource Planning
GHG	Green House Gas
GWP	Global Warming Potential
ICT	Information and Communication Technology
ISO	International Organization for Standardisation
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
LUC	Land Use Change
dLUC	Direct Land Use Change
iLUC	Indirect Land Use Change
MCDM	Multi-Criteria Decision Methods
PCR	Product Category Rules
PED	Primary Energy Demand
PEF	Product Environmental Footprint
SLCA	Social Life Cycle Assessment
SME	Small and medium-sized enterprise
UNEP/SETAC	United Nations Environmental Programme/Society of Environmental Toxicology and Chemistry
WBCSD	World Business Council for Sustainable Development

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